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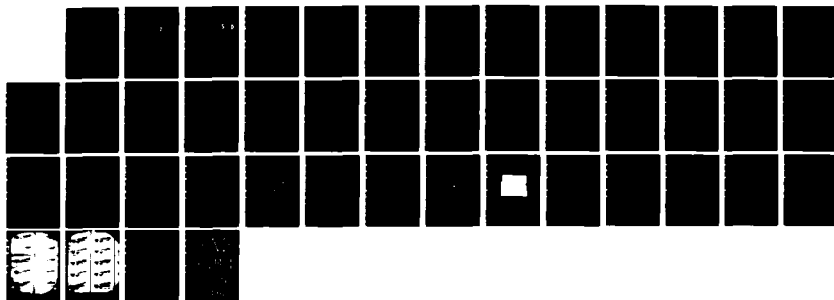
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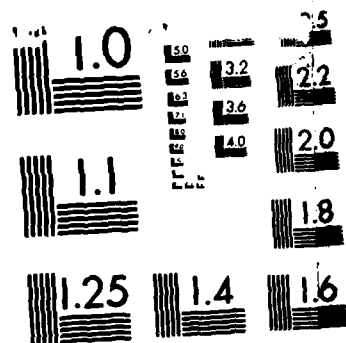
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TRANSIENT COMBUSTION DYNAMICS (U)

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University of Southern California

October 1985

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ABSTRACT

Many dump combustors exhibit low frequency longitudinal combustion instability in the frequency range of 80-300 hz. Although the exact causes of combustion instability are not known precisely, it is generally accepted that the interaction of the shock induced pressure pulsation and the coherent vortex shedding at the dump plane induces combustion instability. During this study a characteristic system frequency associated with sudden expansion steps and a resulting coherent beat phenomenon have been identified. It is also shown that combustion oscillation can occur when the induced forced frequency is approximately equal to the mean of the beat frequency. When the coherence of the shear layer at the dump plane is disrupted either by gasjets or by upstream protrusions the effect of combustion instability is found to be minimized. The control system suggested in this report is based upon the idea of disrupting the shear layer at the dump plane by means of pulsing gasjets. The control system senses the critical combination of frequency, amplitude and phase angle upstream of the combustor and actuates the gasjets at the dump plane at an appropriate combination of frequency, amplitude and phase angle to partially negate the effect of upstream pressure pulsation. Experiments in two laboratory scale two-dimensional (6.4 cm x 3.8 cm and 7.6 cm x 2.54 cm) and a 6.4 cm diameter axisymmetric dump combustors using premixed propane-air mixtures show the feasibility of reducing chamber pressure amplitude by such a technique.

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combination of frequency, amplitude and phase angle to partially negate the effect of upstream pressure pulsation. Experiments in two laboratory scale two-dimensional (6.4 cm x 3.8 cm and 7.6 cm x 2.54 cm) and a 6.4 cm diameter axisymmetric dump combustors using premixed propane-air mixtures show the feasibility of reducing chamber pressure amplitude by such a technique. *Requiescat*

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pairing and the feed back of disturbance to the dump plane. Having checked his postulates with selected available ramjets the author concludes that "the necessary condition for large amplitude oscillations is a resonant vortex interaction/feedback like condition to exist in the chamber".

Although shock perturbation and vortex shedding due to the instability of the shear layer play important individual roles in combustion instability, there are examples of combustion instability induced primarily by spray pattern, injector design and fuel stratification. Ramjet vehicles such as, for example, ASALM (Advanced Strategic Air Launched Missile), LFRED (Liquid Fuel Ramjet Engine Demonstration), Fireband and IBRT (Integral Booster Ramjet Technology) are cases in point. Low frequency combustion oscillation in each of these systems was eliminated simply by changing the fuel distribution and injector characteristics (Ref. 1). Similar solution of combustion oscillation in a laboratory scale side dump combustor has been reported in Ref. 9. Several research projects have addressed the importance of fuel stratification caused by liquid phase pyrolysis and fractional distillation of the fuel blend used in a typical ramjet engine (Refs. 10,11 and 12, for example).

Even though combustion instability problems in ASALM and other ramjets were solved by changing the fuel distribution other prototypes such as LIFRAM (Liquid Fuel Ramjet) and GORJE (Generic Ordnance Ramjet Engine) had severe problems with combustion

instability. Changes in the spray pattern or injector configuration had only a minor effect on the system performance. Eventually both of these two programs were cancelled and further flight tests were postponed indefinitely.

The observed low frequency combustion instability in dump combustors is an extremely complex phenomenon in which the inlet shock perturbation, vortex interaction, chamber acoustics and fuel spray characteristics all play an important role. Most of the investigators select one area at a time in order to obtain an understanding of how each of these separate events contribute to the overall picture. Thus, investigators like those in references 3,4,5 and 6 deal only with shock perturbation and its effect on the flow. Others (Refs. 7,8,13,14 and 15) study only the vortex shedding and its effect on the system behavior.

The present study was aimed at investigating the interactions and combined effects of inlet pressure perturbation and coherent vortex shedding at the dump plane. Also one of the goals of this research project was to suggest a novel workable control system which will help destroy the coherent pressure oscillation in the chamber by altering the shear layer characteristics at the dump plane. Shear layer at the dump plane can be perturbed either by mechanical or fluid dynamic means. Protrusions or notches on the wall ahead of the dump plane can effectively alter the characteristics of the shear layer. However once these are installed in the combustor, disturbance

due to their presence will continue even when such disturbances are not needed. The gasjet system (fluid dynamic method), on the other hand, does not disturb the flowfield until it is activated. Therefore, the fluid dynamic means of destroying the coherence of the shear layer is preferable. Under certain operating conditions, the use of gasjets upstream of the dump plane as a means of altering the shear layer characteristics and increasing the size of the recirculation zone has a marked influence on the combustor performance. Rough burning caused by fuel stratification as well as by a constrained recirculation zone can be smoothed out and the combustor performance increased by the use of these gasjets (Refs. 16 and 17).

Two small two-dimensional (6.4 cm x 3.8 cm and 7.6 cm x 2.54 cm) channel and a 6.4 cm diameter axisymmetric burners were used for studying the combustion oscillation and the novel method of minimizing these oscillations by means of pulsating gasjets. Since the combustible mixture was premixed (gaseous propane-air mixtures), combustion oscillation associated with fuel stratification did not arise allowing one to focus on the problem of interaction between the inlet pressure oscillation and the coherence of vortex shedding. Smaller chambers are ideal tools for studying such a problem because it is known that smaller chambers are more prone to low frequency combustion instability (Refs. 1, 18 and 19).

2. EXPERIMENTAL PROGRAM

2.1 Appatatus: Two channel shaped 6.4 cm x 3.8 cm, chamber B and 7.6 cm x 2.54 cm, chamber A and a 6.4 cm diameter axisymmetric combustors with variable sudden expansion steps were used for studying the effect of upstream pressure pulsation. Premixed propane-air mixtures were used in all the combustion experiments. Figure 1 is a sketch of the smaller channel burner (chamber A) showing the location of the system of gasjets upstream of the dump plane. Figures 2 and 3 show the combustion facility and the air bypass for introducing variable amplitude and variable frequency pulsations in the flow field. As the holes in the cap and the bypass tube (Fig. 3) line up more air passes through the bypass and the pressure in the system drops momentarily. The pressure increases as soon as the flow is blocked during the rotation of the cap located at the end of the bypass tube. The amplitude of the induced pressure pulsation in the chamber can be changed by the valve in the bypass line. The frequency of pressure pulsation can be changed by changing the speed of the motor which rotates the cap. The frequency can also be changed by changing the number of holes in the cap.

The range of frequency where control is needed for minimizing the effect of combustion instability is approximately between 50 and 200 hz. These frequencies are too large for any commercial solenoid air valve to operate reliably and in a satisfactory manner. Therefore, a rotating teflon valve shown in

Fig. 4 was used for providing the necessary pulsing of the gasjets upstream of the dump plane. The valve stem is attached to a D.C. motor and the rotational speed of the motor is proportional to the on and off cycle of the valve. The valve shown in Fig.4 has its hole lined up with the inlet and the exhaust. At this point the gas flows through the valve. The flow stops when the stem rotates and the hole is not lined up to the inlet and the exhaust tubes. Although compressed air at ambient temperature was used in the gasjets for most of the experiments, heated air, oxygen or even fuel-air mixture can be used for dramatically increasing the effectiveness of the system. The mass flow rate of the jet gas was typically between 1% to 4% of the primary air.

A DEC LSI 11/23 computer with 16 channel A to D and D to A controller was used for most of the data processing. In addition, pressure transducers, frequency analyzer, a variety of electronic equipment, shadowgraph and schlieren system and also both still and high speed movie (Fastax) cameras were used.

3. RESULTS AND DISCUSSION

3.1 Chamber Response: Violent combustion oscillation and flame blowoff were observed in the smaller chamber (chamber A) when the upstream pressure was pulsed in the frequency range of approximately 60 to 100 hz. Combustion oscillation seemed to disappear for both higher (upto 500 hz) and lower pulsing frequencies. The critical frequency range remained the same even after the natural frequency of the system was changed by changing the overall length of the system by more than 30%. Further investigation showed that at the critical frequency the pressure amplitude must exceed a limiting value before combustion instability can set in. Figure 5 shows the chamber response of the smaller combustor (chamber A) and the region where the upstream pulsing was found to induce combustion oscillation. Although it appears from the figure that the combustion instability coincides with the overall system resonance, further investigation in both the chambers shows that the critical frequency can be different than the resonance frequency. Figure 6 shows the response of chamber B and the critical frequency range where combustion oscillation was observed.

3.2 Step Generated Characteristic Frequency and Beating: In order to understand why a certain combination of frequency and amplitude of the inlet pulsing is able to induce combustion oscillation, the pressure-time and pressure-frequency history in the vicinity of the step were investigated. PCB pressure

transducers for low frequency pressure pulsations, located in and around the dump plane show that the shear layer instability has a characteristic coherence even without the induced pulsing at the inlet. The coherence appears in the form of low frequency "beating" which is easily visible on the p-t history whenever there is a sudden expansion step. It is believed that multiple vortex system originating from fuel injector, igniter and various protrusions in the system interact and eventually cause beating. Thus, it was necessary to isolate each component one at a time to narrow down the probable source of beating. In the present combustor systems the mean beat frequency approximately coincided with the critical frequencies at which the combustion oscillation was observed. In other words, when the external flow pulser was allowed to pulse the flow at the critical frequency, combustion oscillation resulted only if the pressure amplitude exceeded a certain minimum value (Fig. 5). This is consistent with the practice of rating combustion chamber stability by using the minimum pulse strength necessary to drive the system unstable. (THEY DO THIS IN ROCKETS:- "BOMBING"). In order to find the source of the very important beat phenomenon, system components such as exhaust pipe, fuel injector, valves etc. were taken out one at a time. Additional plenum chambers were added to damp out the disturbance from the blower. As a final measure the test section was attached to the air inlet of the blower so that the undisturbed ambient air will enter the test section first before entering the blower.

Results of these tests under cold flow conditions show that for each chamber the disturbance due to the sudden expansion step has a mean center frequency which is relatively insensitive to changes either in the step height or the flow speed. Figure 7, for chamber B shows the effect of covering up the step so that instead of a sudden expansion the flow passes over a flat plate. In the absence of a step the disturbance at the characteristic frequency disappears and only the background noise is observed. Even a very small perturbation at the step location causes the disturbance to reappear at the same observed frequency. Figure 8 is a schematic of the characteristic frequencies in all the burners under investigation. Figure 9 shows traces from a frequency analyzer for three flow speeds in chamber B with a 1.3 cm step. The center frequency between 1800 and 1900 hz remains essentially unchanged. But the amplitude and the details inside the bandwidth change with flow speed. Closely spaced amplitude spikes in the frequency domain are responsible for the coherent beating. If the signal is processed through a bandpass filter between 1600 and 2200 hz, for example, the beats are clearly visible on a p-t trace. Figure 10 shows such a p-t trace for chamber B with a flow velocity of 74 m/s. Beating was found in all the systems centered around their own step induced characteristic frequencies. For chamber A the characteristic frequency was around 1500 hz and for a 6.4 cm diameter axisymmetric chamber it was around 2300 hz. Beating was observed for both hot and cold flows when the signal was processed through a bandpass filter. For a given chamber the mean of the

distribution of beat frequencies is observed to correspond roughly to the critical frequency at which the combustion oscillation starts.

The existence of such a coherent beat phenomenon and the importance of its frequency distribution to low frequency combustion oscillation have not been reported earlier in the open literature. Figure 11 shows the distribution of beat frequency in chamber B under cold flow conditions from a photographic study of the beats on the p-t trace. In this case the chamber was attached to the inlet section of the blower. Figure 12 corresponds to the case where the chamber was attached to a straight pipe without any venturi, valves or fuel injection system. Figure 13, on the other hand, shows the combined effect of the interaction between the vortices from valves, fuel injectors etc. Combustion oscillation in this chamber appears in the vicinity of 120 to 180 hz. Although data processing for hot flow was not completed, preliminary observation shows a similar distribution for the case of the reacting flow. The beat frequency is much lower than the center frequency (Fig. 9) about which the beating originates. Figure 14 shows the beat frequency distribution in the axisymmetric chamber.

3.3 Probable Causes of the Characteristic Frequency: It was not clear why each of the chambers with a step has a specific characteristic step induced frequency. Disturbances at the

characteristic frequency disappears as soon as the step is covered up (i.e., the case of a flat plate). It reappears as soon as a sudden expansion step is introduced. For smaller step heights the amplitude is small but the frequency remains essentially unchanged. Also the frequency is independent of the transducer location inside the recirculation zone. These frequencies are not the periodic vortex shedding frequencies which are usually correlated using Strouhal number (Ref. 20). Correlations of this type yield frequencies which are proportional to the free stream velocity V . Figure 9 shows that such a dependence does not exist for the present characteristic frequencies. Reference 14 shows the variation of the mean time interval for vortex formation in a dump combustor as a function of the flow speed. The frequency of vortex formation due to the step was shown to be proportional to $V^{0.68}$. Therefore, the present characteristic frequencies of 1500, 1900 and 2300 hz do not appear to be due to the formation of vortices at the sudden expansion step. This emphasizes the need to study mechanisms other than vortex shedding so that a better understanding of the instability phenomenon is obtained.

As indicated earlier, the mean of the beat frequencies appears to coincide roughly with the critical frequency of combustion oscillation. Pulsing of the inlet can reinforce the "beating" when the frequency, amplitude and the phase between the signals are "correct". If the vortex pairing and signal feedback concept of Ref. 8 is used, the approximate predicted critical

frequency of the system becomes 260 hz. Also the large scale vortex pairing concept of Ref. 7 predicts a frequency of around 300 hz where combustion oscillation in the two-dimensional chamber could occur. A study of Figs. 5 and 6 show that inlet pulsing at neither of these two frequencies caused any combustion oscillation. Although the hydraulic diameter of the two-dimensional chambers were used for computing the frequencies it is possible that the approximate theories of Refs. 7 and 8 do not apply to channel burners.

3.4 Control System Concept: Reference 16 has shown that if the characteristics and the coherence of the shear layer at the dump station is changed by means of either gasjets or by upstream protrusions, the effect of combustion instability can be minimized. Using this line of reasoning a feedback control system for minimizing the effect of combustion oscillation had been proposed first in Ref. 21. The control system senses the critical combination of frequency, amplitude and phase angle of the inlet pressure perturbation and pulses the gasjets (Fig. 1) at an appropriate combination of frequency, amplitude and phase angle so as to change the characteristics and coherence of the shear layer. The phase of the pulsing gasjets is very critical. An incorrect phase angle will enhance combustion oscillation rather than minimizing it.

Substantial reduction of pressure amplitude was observed when pulsing gasjets were used. Figure 15 shows a factor of 2.5

reduction of amplitude when the gasjets are allowed to pulse at approximately 100 hz, i.e., near the mean of the beat frequency distribution (Fig. 11). Pulsing at around 30 hz produced only a small reduction in the pressure amplitude. The teflon valve failed when a pulsing frequency in excess of 110 hz was attempted. It is being redesigned with proper cooling for further tests at higher frequencies. The results shown in Fig. 15 prove the feasibility of the concept first proposed by the authors (Ref. 21). At the time of this writing the feedback loop is not in operation. The gasjets were simply pulsed at a constant rate with shop air at the operating point where the combustor is known to have problems. Experiments were also performed with continuous rather than pulsing gasjets. Continuous gasjets are equally effective in reducing the amplitude at the characteristic frequency.

3.5 Behavior of the Recirculation Zone: Shadowgraph and direct motion pictures at approximately 1000 frames per second clearly show that the recirculation zone undergoes periodic pulsations when the upstream pressure is allowed to oscillate. The flame appears to alternate between a near blowoff to a near stable condition in phase with the oscillation of the recirculation zone. There is a distribution of oscillation frequencies which appears to be of the same order of the distribution of the inlet pulsing frequency. Detailed characterization of the frequency response of the recirculation zone was not carried out during the course of this study.

With continuous as well as pulsing gasjets the recirculation zone seemed to become somewhat isolated from the periodic disturbance of the free stream and consequently did not show oscillations of large amplitude. The effect of the gasjets is to introduce damping in the system and thereby reduce the amplitude of oscillation of the recirculation zone. A gasjet system pulsing out of phase, in principle, will be able to provide the maximum damping. Since the detailed design of the control system is beyond the scope of this study no attempt was made to control the phase angle of the gasjets. A gasjet system flowing continuously at a pressure of .1 to .14 MPag was able to provide an acceptable level of damping

Figure 16 is a sequence of 1000 frames/s pictures showing the pulsation of the recirculation zone and the near blowoff to near stable behavior of the flame in chamber B subjected to an upstream pressure oscillation of approximately 80 hz. This frequency is slightly below the critical frequency of the chamber. Figure 17 shows the effect of a continuous gasjet (.14 MPag) on the recirculation zone in the same chamber subjected to the same upstream periodic disturbance. Because of the increased damping in this case, the amplitude of pulsation of the recirculation zone has decreased considerably and as a direct result the flame appears to be much more stable.

The experiments reported here corroborate further the importance of the observed beat phenomenon and the distribution of beat frequencies (Fig. 13). The existence of a characteristic frequency in a dump combustor and the phenomenon of beating centered around that frequency are very important in the general area of combustion instability

4. CONCLUDING REMARKS

1. This research project has identified characteristic system frequencies associated with sudden expansion steps and the resulting coherent beat phenomenon which helps induce combustion instability. From the beat frequency distribution it is possible to predict the range of frequencies where combustion instability is likely to occur in a particular dump combustor.

2. The present work has demonstrated the feasibility of the concept of feedback (or feed forward) control loop which senses a critical combination of upstream disturbance and destroys the coherent periodicity of the shear layer at the step by means of pulsing gasjets. Pulsing gasjets can be used either upstream or inside the recirculation zone to minimize the effect of combustion oscillation both in axial and side dump (Ref. 21) combustors. A correct phase angle, however, is extremely important.

3. The fact that the characteristic step induced frequency was observed to be insensitive to the velocity, step height and the location within the recirculation zone causes one to believe that the response of the recirculation zone (homogeneous reactor) to the periodicity of the shear layer might very well be responsible for the frequency. Both direct pictures and shadowgraphs at 1000 frames/sec show that the recirculation zone undergoes periodic pulsation when the upstream pressure is allowed to oscillate.

5. FUTURE WORK

Logically, the next phase of the study should include larger combustors with realistic operating conditions and choked nozzles. Since the work reported here was carried out in laboratory scale burners at atmospheric pressure, the follow on work on larger burners must proceed so that the conclusions of this study can be validated.

At the same time research on smaller combustor should continue so that the causes of the characteristic frequency and the resulting coherent "beating" can be understood.

The response of the recirculation zone subjected to forced vibration due to inlet pulsing should also be studied analytically.

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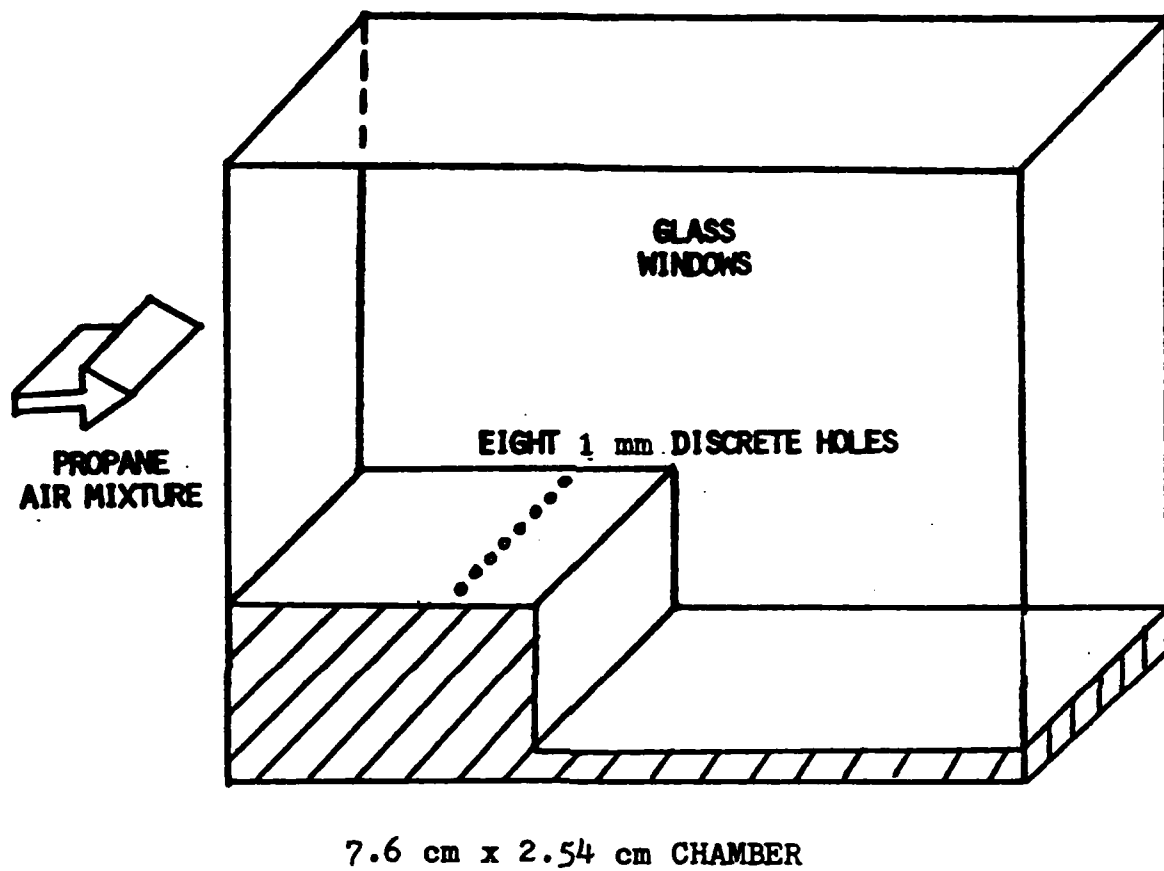


FIGURE 1. Sketch of 2-D chamber A.

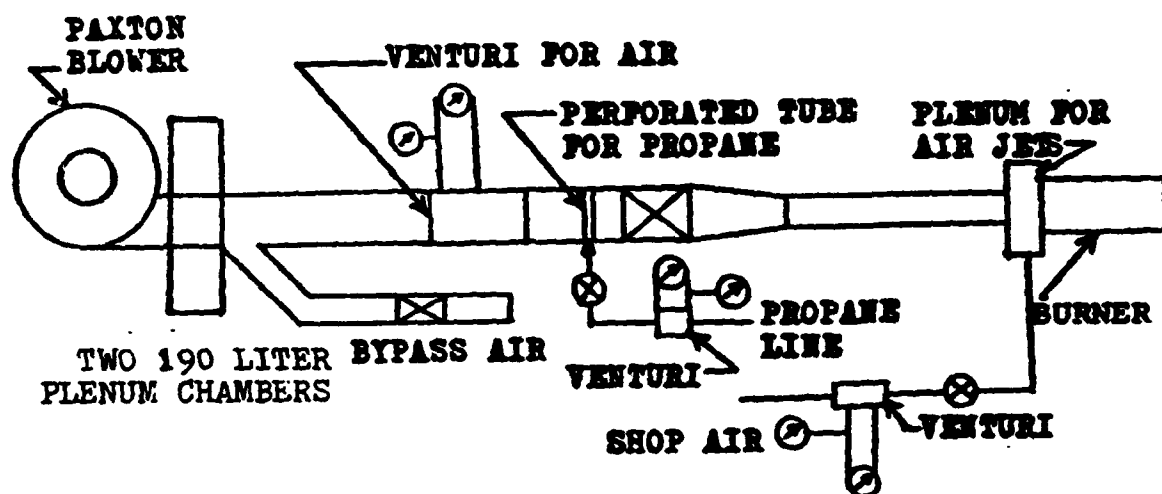


FIGURE 2. Sketch of the combustion facility.

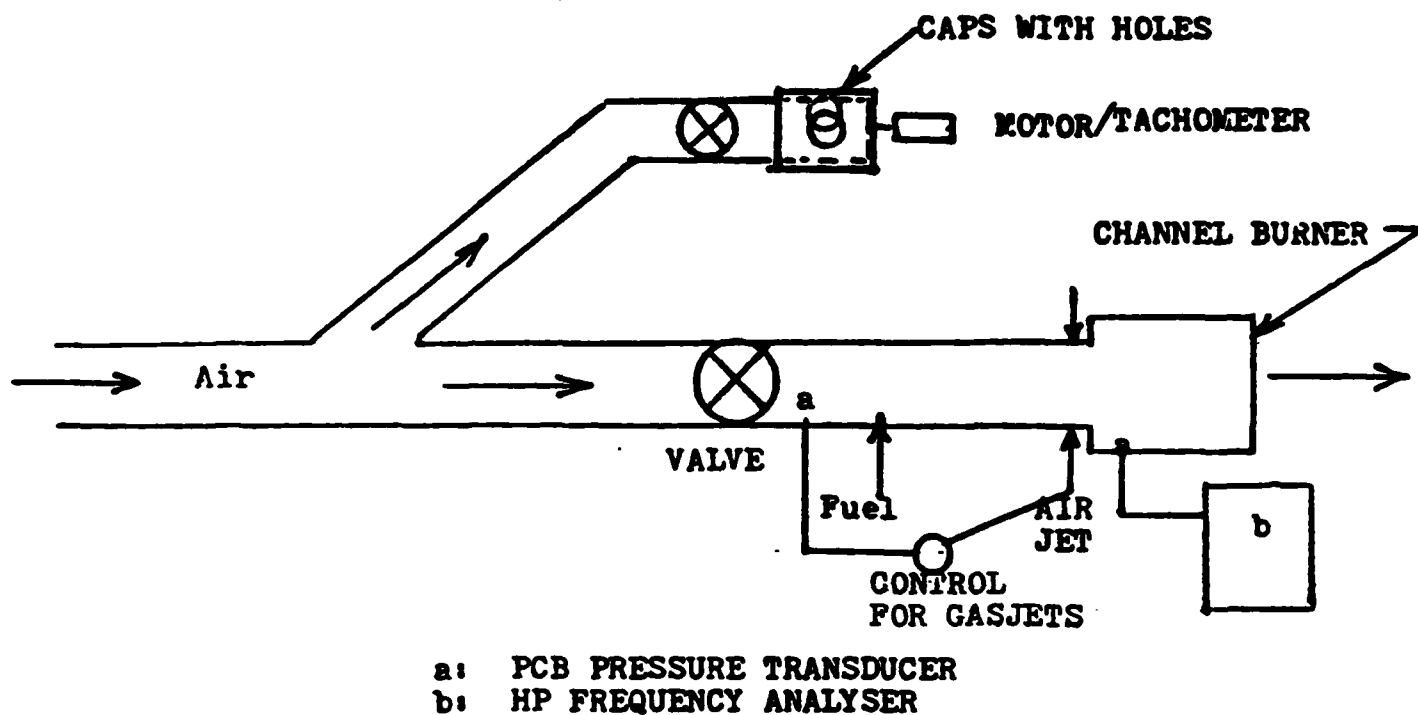


FIGURE 3. Schematic of the system with the pulser and control system.

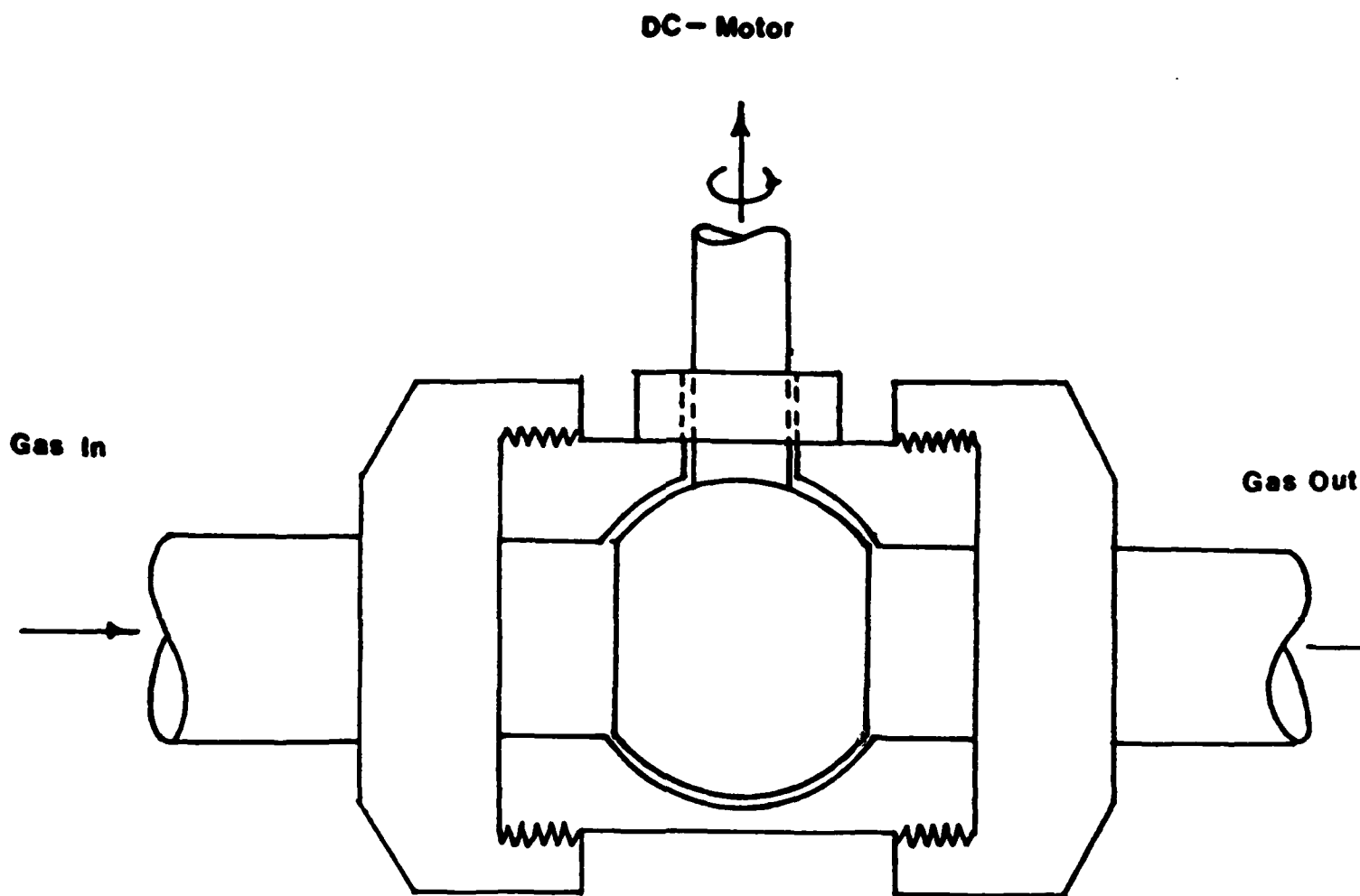


FIGURE 4. Rotary teflon valve for pulsing gasjets.

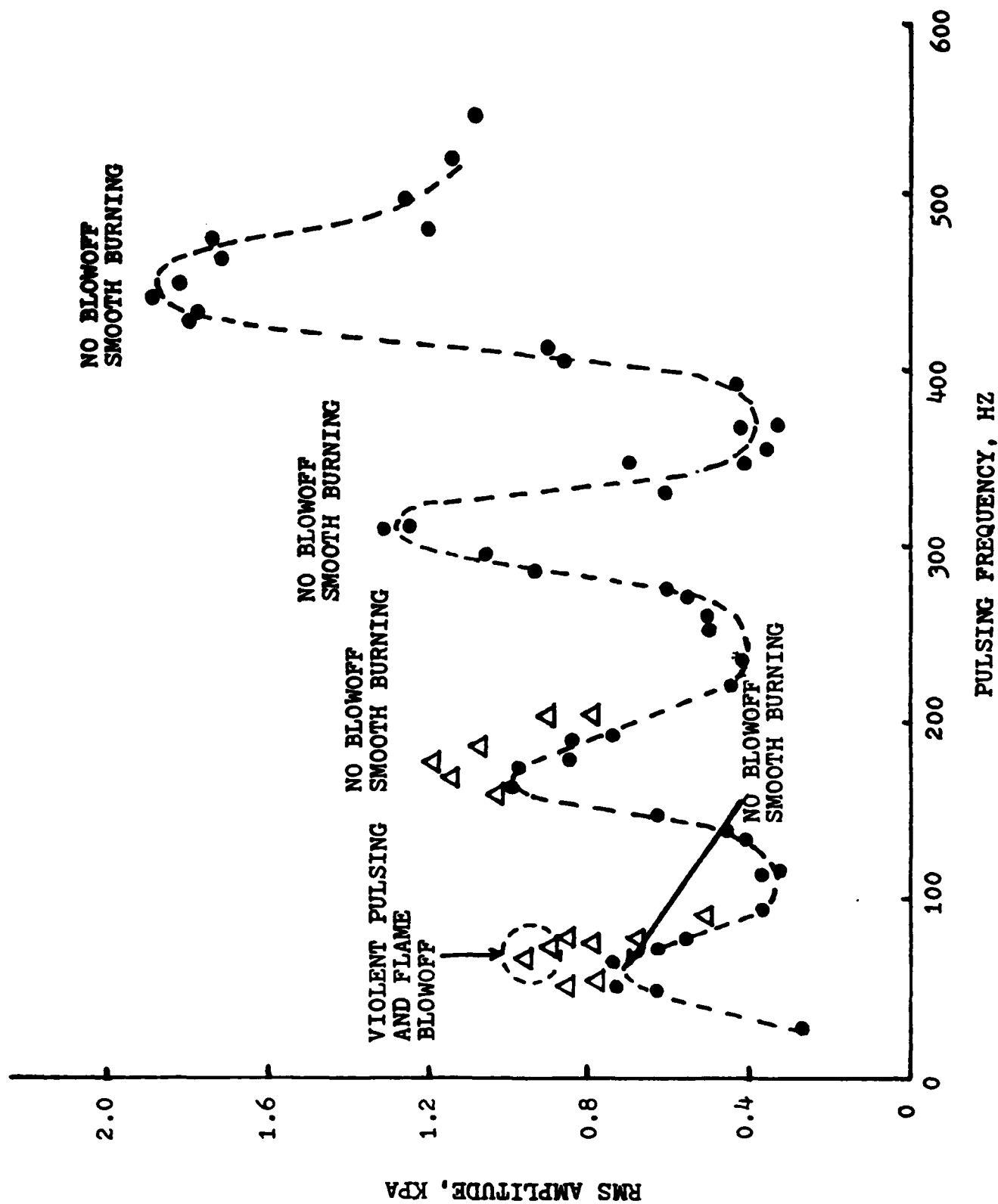


FIGURE 5. Chamber response to inlet pressure pulsing. Chamber A, 1.3 cm step.

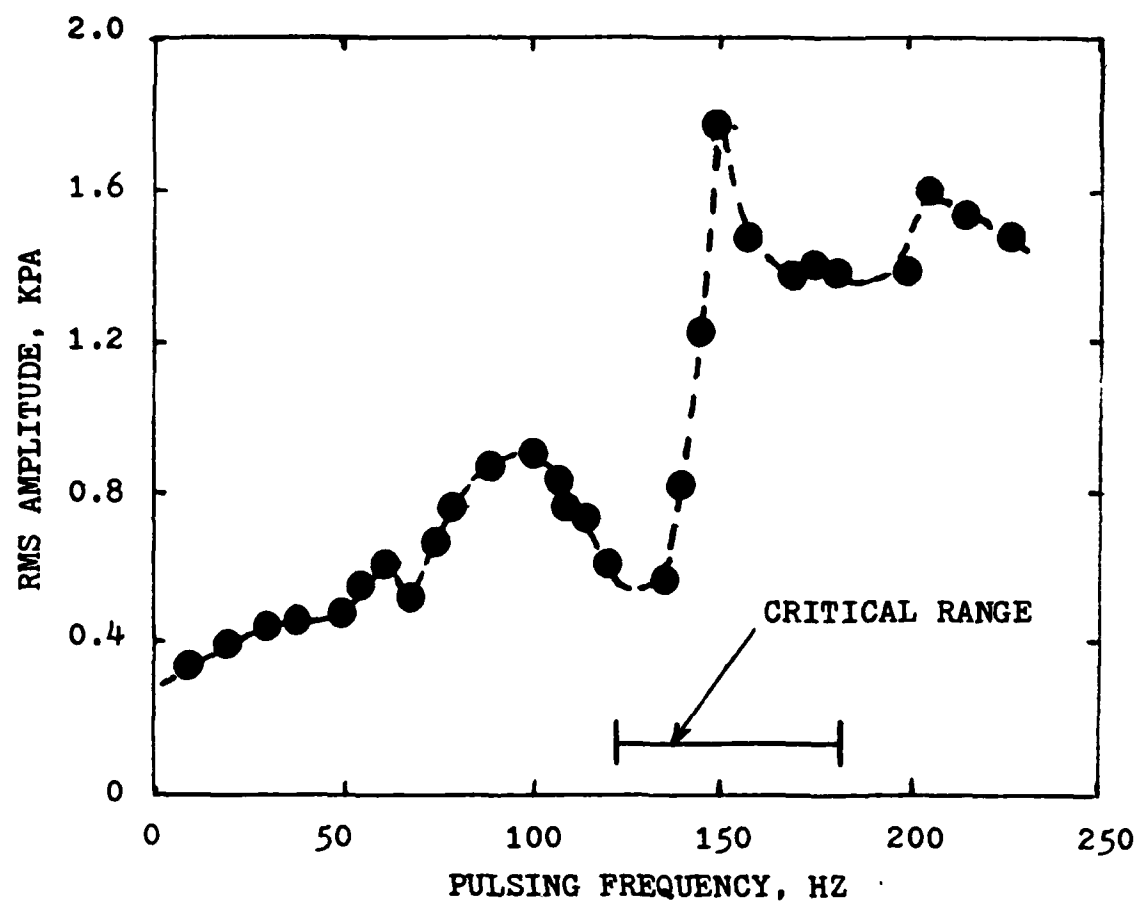


FIGURE 6. Response of chamber B to inlet pressure pulsing.
1.3 cm step, cold flow, 56 m/s.

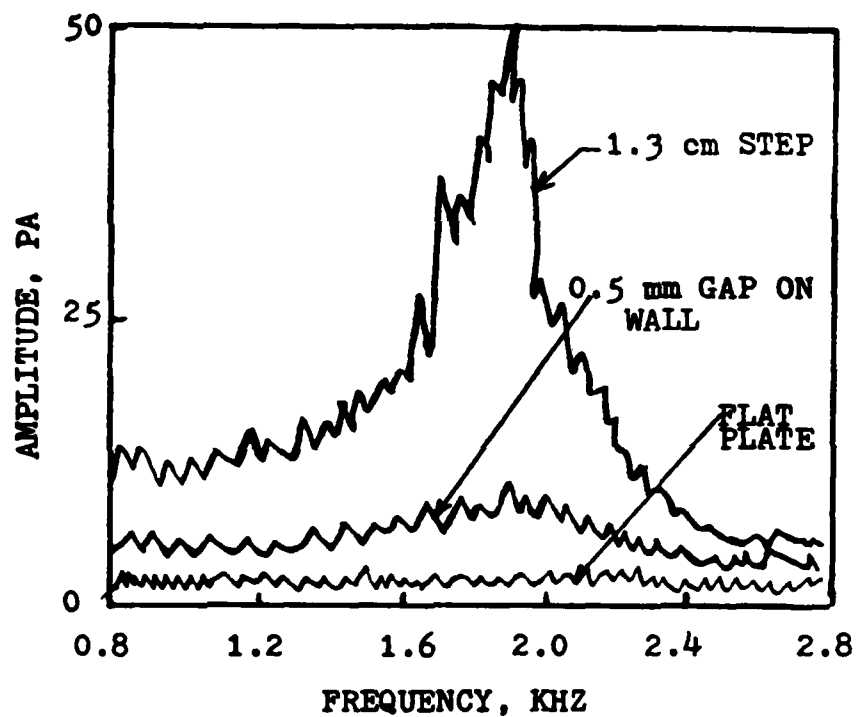


FIGURE 7. Effect of step height on step generated characteristic frequency, chamber B, cold flow, 74 m/s.

CHAMBER B, 1.3 cm STEP

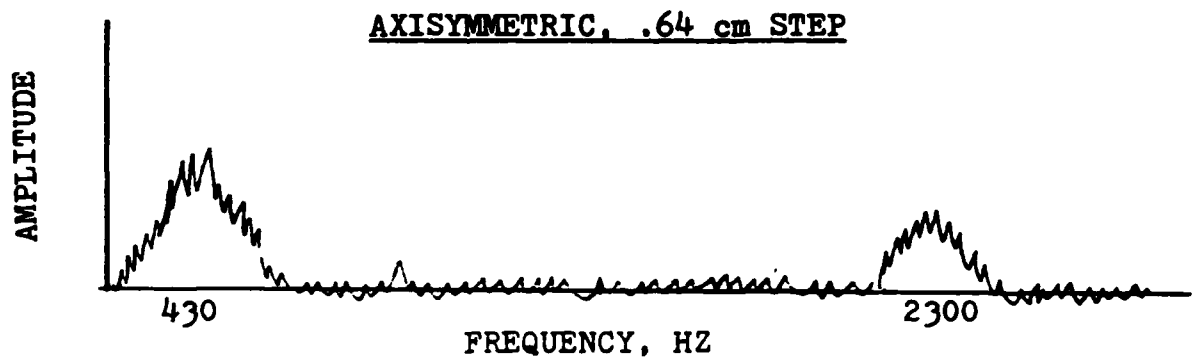
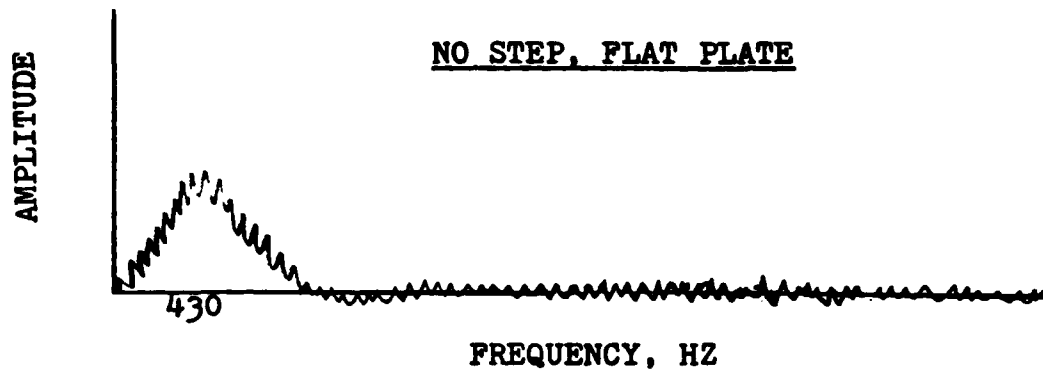
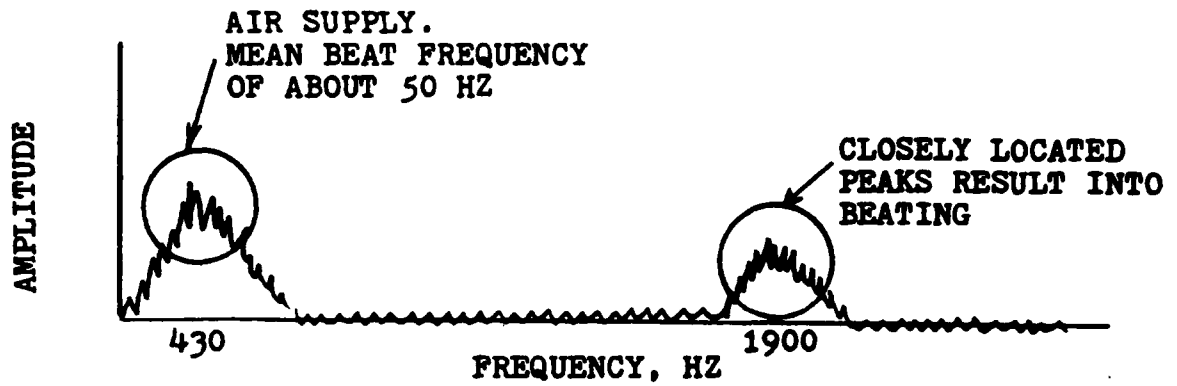


FIGURE 8. Schematic of the step generated frequencies.

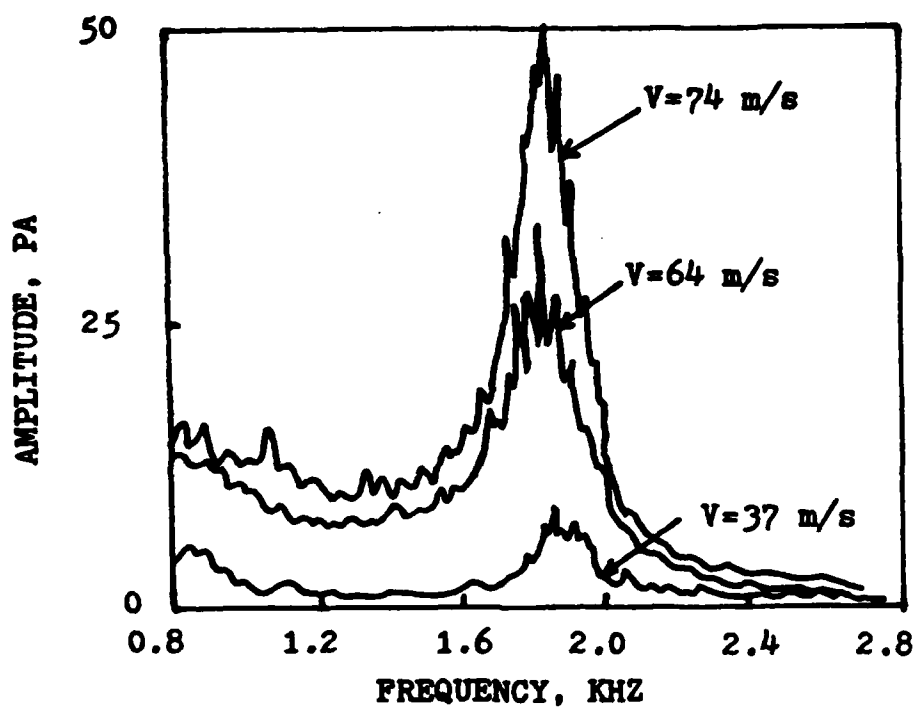


FIGURE 9. Effect of velocity on the step generated characteristic frequency and amplitude. Chamber B, 1.3 cm step. Cold flow.

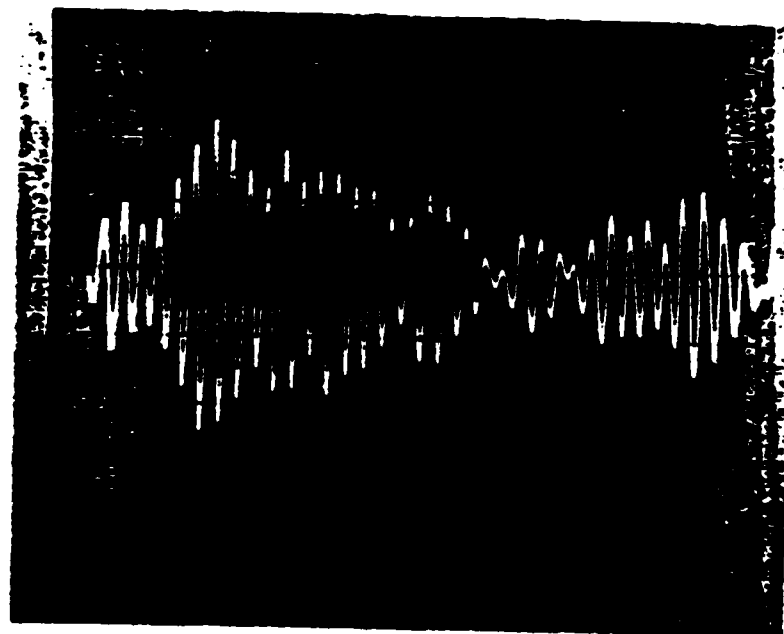


FIGURE 10. p-t trace of the beat phenomenon in chamber B,
Cold flow. 1.3 cm step. Filter: 1600-2100 hz.
74 m/s

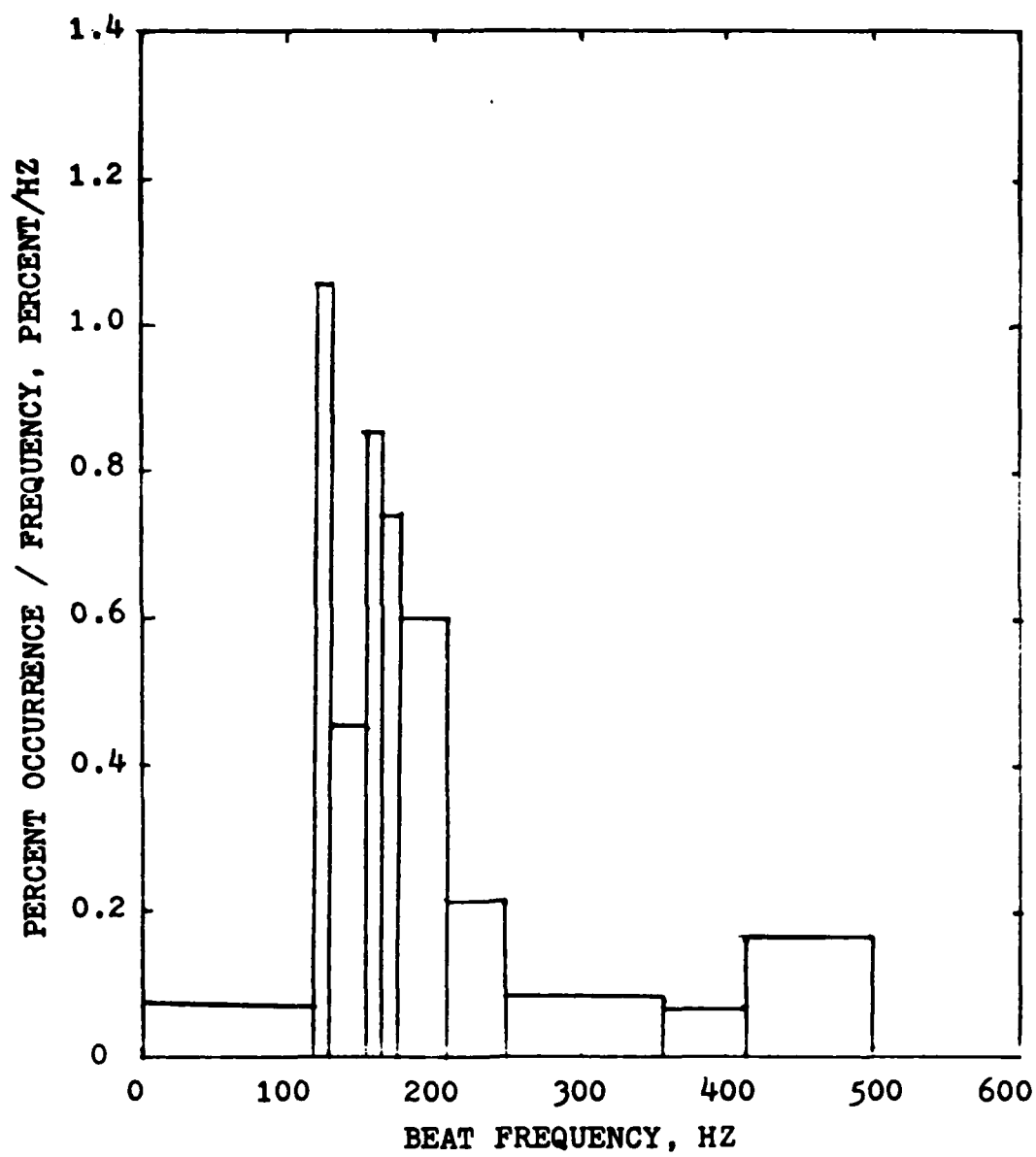


FIGURE 11. Beat frequency distribution in chamber B located at the blower inlet. Filter: 1600 - 2000 hz, 74 m/s.

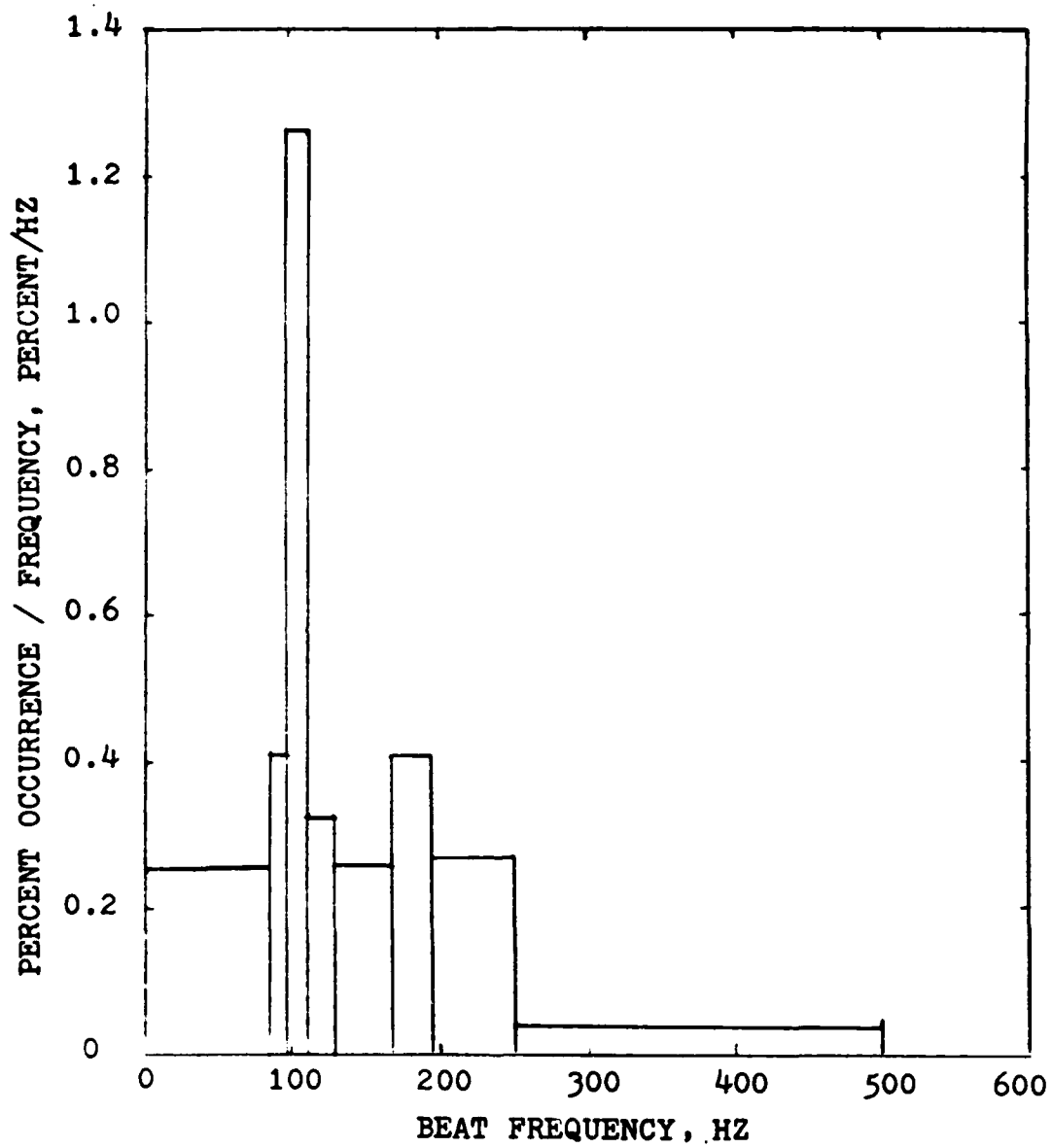


FIGURE 12. Beat frequency distribution in chamber B in a bare straight pipe. Filter: 1600 - 2000 hz. 74 m/s.

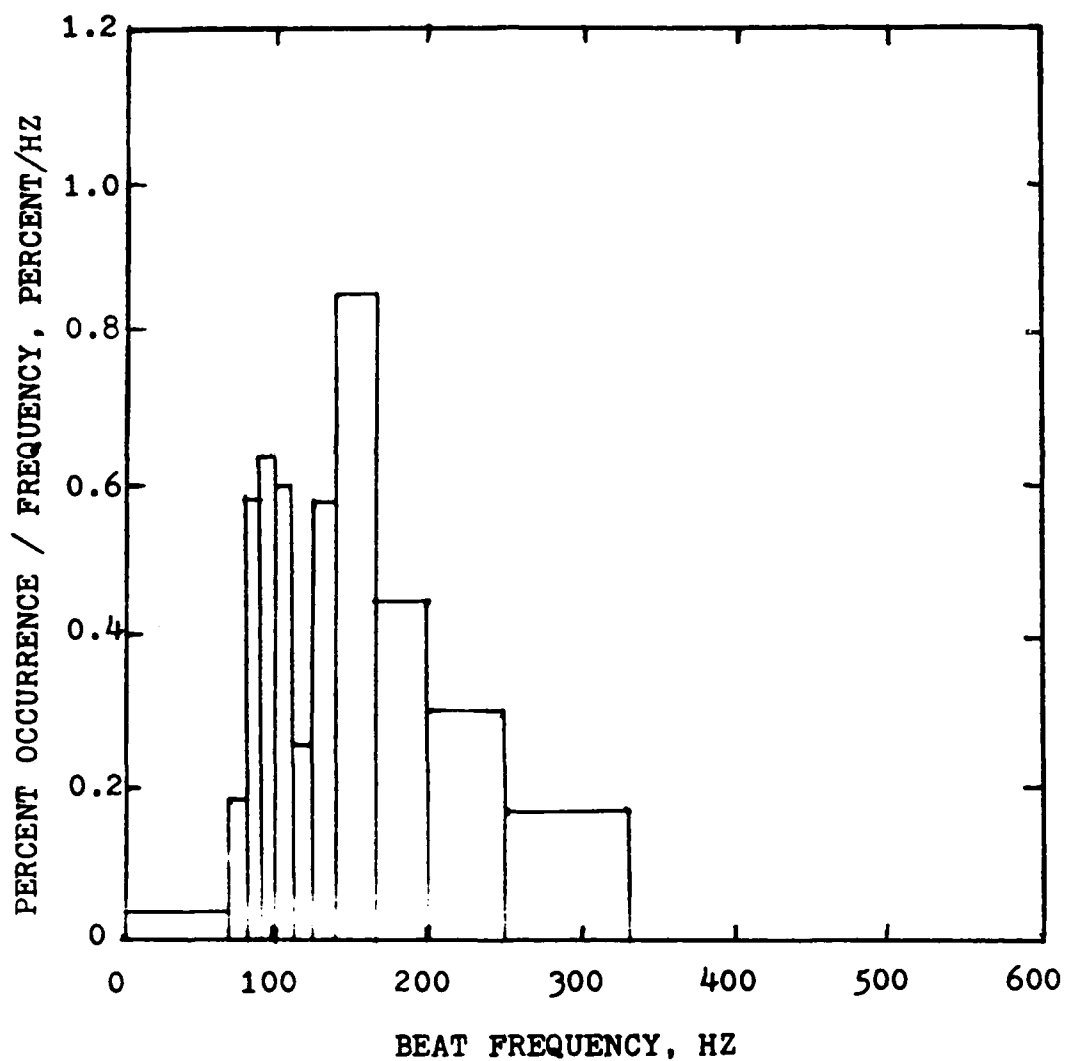


FIGURE 13. Beat frequency distribution in chamber B as installed in the system. Filter: 1600 - 2000 hz, 74 m/s, cold flow.

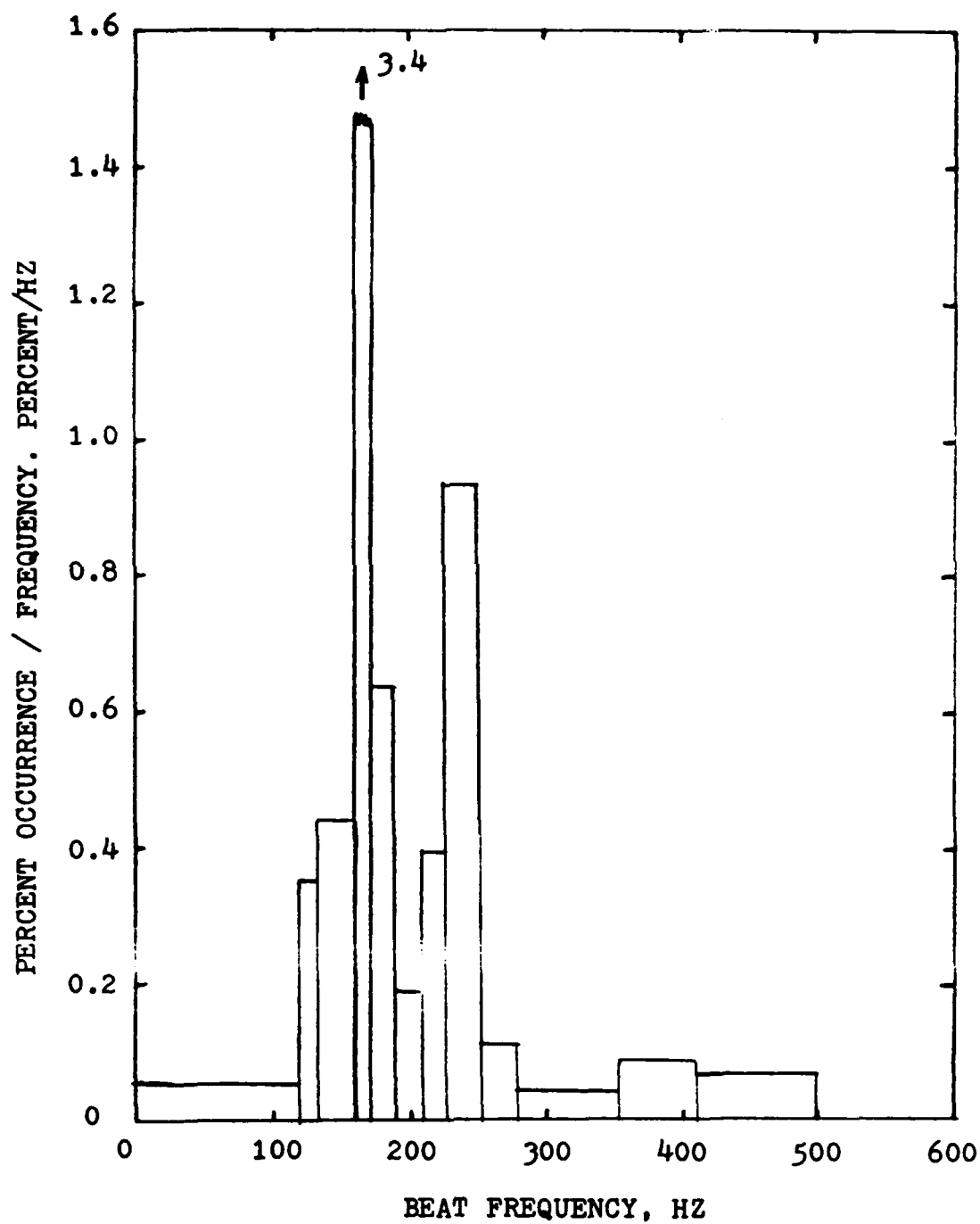


FIGURE 14. Beat frequency distribution in the axisymmetric chamber, .64 cm step. Filter: 2100 - 2500 hz, 65 m/s.

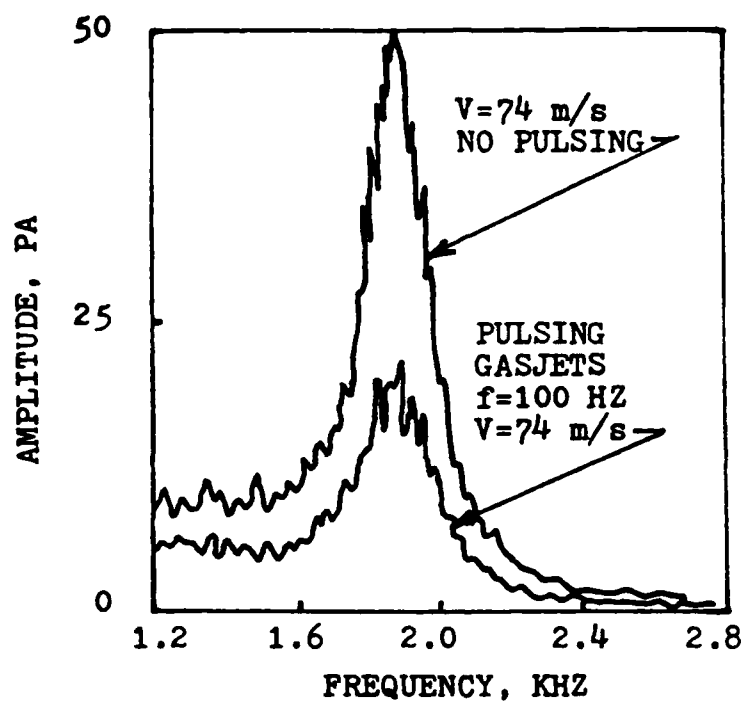


FIGURE 15. Amplitude reduction at the step generated characteristic frequency caused by pulsing gasjets. Chamber B, 1.3 cm step. Cold flow



FIGURE 16. A sequence of 1000 frames/s pictures. Inlet pulsing frequency ~ 80 hz. Chamber B. 40 m/s. Equivalence ratio $\sim .8$



FIGURE 17. Effect of continuous gasjets (.14 MPag) on the flame and the recirculation zone. 1000 frames/s. Inlet pulsing frequency ~ 80 hz. Chamber B. 40 m/s. Equivalence ratio $\sim .8$

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PRESENTATION AND/OR PUBLICATION

1. 1983 AFOSR Contractors Meeting, (2 talks) Scottsdale, Arizona, September 19-23, 1983.
2. 1984 ONR/NAVAIR Ramjet Combustion Instabilities Conference, Naval Post Graduate School, October 24-25, 1984.
3. Choudhury, P. Roy, Gerstein, M. and Mojaradi, Reza, "A Novel Feedback Concept for Combustion Instability in Ramjets" 22nd JANNAF Combustion Meeting, Jet Propulsion Laboratory, Pasadena, October 7-11, 1985. To be Published in CPIA publication for the 22nd Combustion Meeting.

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